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Design and Measurement of a Cu L-edge X-ray Filter for FEL-Pumped X-ray Laser Experiments [a)]

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An inner-shell photo-ionized x-ray laser pumped by the Linac Coherent Light Source (LCLS) free electron laser has been proposed recently. Measurement of the on-axis 849 eV Ne Kα laser and protection of the x-ray spectrometer from damage require attenuation of the 1 keV LCLS beam. An Al/Cu foil combination is well suited, serving as a low energy bandpass filter below the Cu L-edge at 933 eV. A high resolution grating spectrometer is used to measure the transmission of a candidate filter with an intense laser-produced x-ray backlighter developed at the LLNL Jupiter Laser Facility Janus. The methodology and discussion of the observed fine structure above the Cu L-edge will be presented.

I. INTRODUCTION

The Linac Coherent Light Source (LCLS) is a recently completed free electron laser (FEL). The ultra-short high brilliance x-ray pulses enable a new generation of ultrafast x-ray pumping, probing and heating experiments.[1] Recently an experiment has been proposed to improve the coherence and temporal parameters of the FEL and test atomic kinetics models by generating an inner-shell photo-ionized x-ray laser (ISPXRL) pumped directly by the LCLS beam.[2] The Ne Kα transition at 848.6 eV [3] as well as low charge state n = 2 – 1 lines can be potentially pumped by single pulses of photon energy of 1 keV and sub-100 fs duration by focusing the FEL beam into a neon gas cell at high irradiance > 10^{17} W cm^{-2}.[2] The amplified x-ray laser line and the unconverted FEL beam co-propagate out of the gas cell and would be measured on-axis using a grazing incidence grating soft x-ray spectrometer.

One concern, and the main topic of this paper, is that the FEL beam, at high fluence ~250 mJ cm^{-2}, will damage instrumentation at 1 meter from the gas cell, see Figure 1 for the proposed ISPXRL experiment. Since the FEL beam is focused using *f/1000* B_4C-coated Kirkpatrick-Baez mirrors to 1 – 2 µm diameter spot size in the gas cell, this beam continues to diverge after the gas cell at a ~1 mrad angle. The estimates of damage threshold, discussed in the next section, show that medium- and high-Z materials, e.g. the nickel substrate of the slit assembly and the gold grating, can be damaged at 1 m distance. Therefore, a way of reducing the FEL beam intensity after the gas cell is required to prevent damage to the spectrometer optics and saturation of the detector system. The use of a differential or low energy pass filter to attenuate the 1 keV FEL beam but pass the lower energy Neon Kα x-ray laser has been chosen for ease of manufacture, low cost and overall simplicity. The use of a filter material with the correct K- or L-edge[4] energy position and thickness can be chosen to match the energy band of interest and to maximize the relative attenuation factor β, defined as the transmission ratio T_{XRL}/T_{FEL}, to be as high as ~10^3.[5]

The attenuation of the FEL beam after pumping the x-ray laser is critical for the above experiment, and so, in this paper the design and characterization of the filter is addressed in detail. Cu has the L-edge in the correct energy range for attenuation of the 1 keV FEL beam. Furthermore, we have recently conducted experiments using thin Cu foils irradiated with high power laser pulses in order to study heating and energy transport mechanisms. Thermal emission viewed from behind the target in the 0.5 – 2.0 keV energy band is attenuated by the Cu L-edge as

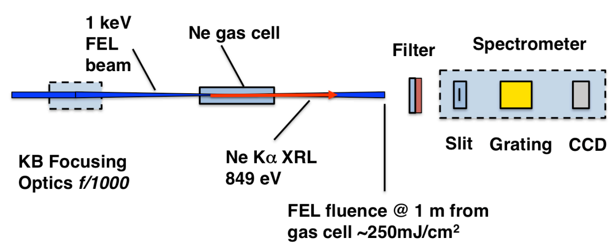

FIG. 1. Proposed inner-shell photo-ionized x-ray laser using the 1 keV LCLS free electron laser (FEL) beam to pump a Ne gas cell and generate a Ne Kα x-ray laser at 849 eV. A filter is required to attenuate the FEL, but pass the ISPXRL beam, to prevent damage to the spectrometer components.

the foil undergoes rapid heating and ionization.[6] A careful measurement of the room temperature Cu L-edge response as a reference point for the thermal transport experiments is another reason for this study.

We discuss the filter selection, the characterization of the transmission response using a laser-produced plasma x-ray source and the interpretation of the results. The conclusion is that extended x-ray absorption fine structure (EXAFS) does not allow as much attenuation in the x-ray signal above the L-edge as initially predicted. Secondly, very small defects or pinholes in the Cu filter structure can have a significant effect here and result in a further reduction in the required attenuation factor β.

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II. FILTER DESCRIPTION

The filter design was based on the Lawrence Berkeley National Laboratory (LBNL) Center for X-ray Optics (CXRO) photo-absorption database,[5] as described in the work by Henke *et al.*.[7] The main requirements for the filter were: (a) Attenuate the FEL beam at 1 keV to a fluence below the damage threshold of the spectrometer components; (b) Ensure that the filter itself not be damaged by the FEL beam; (c) Reduce the signal at the spectrometer charge-coupled device (CCD) detector below the saturation threshold (typically ~ 20 – 50 nJ/cm^2); and (d) Preferentially attenuate the FEL beam more than the Ne Kα ISPXRL line by the attenuation factor β. Cu was a good candidate since it had the L-edge at 932.7 eV and would therefore strongly attenuate the FEL beam. The absorbed energy and dose leading to melt and damage was estimated for Al, Cu and various materials at different positions of 1 – 4 meters after the gas cell. The dose D, defined as the absorbed energy in eV/atom), was calculated from the simple relation $D = \mu_a M_a F$ where μ_a is the absorption cross-section per-unit-mass, M_a is the mass-per-atom and F is the pulsed fluence (energy/area). Low-Z materials received low dose values while mid-Z and high-Z materials had high dose values due to their higher absorption. At 1 meter from the gas cell the dose from the FEL beam and (melt threshold) for Al and Cu were 0.04 eV/atom (0.3 eV/atom) and 0.88 eV/atom (0.44 eV/atom), respectively. The aluminum would survive but the dose on the Cu would exceed the melt temperature and would likely be damaged. For a slit substrate made from Ni similar damage would occur at 1 m. A calculation for a gold surface inclined at 1° to the FEL beam, to model the spectrometer grating angle, gave a dose (melt threshold) of 0.296 eV/atom (0.34 eV/atom). It is clear that neither the instrument components nor the filter could be placed at 1 m from the gas cell without being damaged. The doses at 2 m and 4 m would be 4 and 16 times lower. A bi-layered filter composed of Al/Cu was chosen where 2 µm Al coated with 0.9 µm Cu gave an estimated attenuation ratio β ~900.[5] The Al layer would face the FEL beam and reduce the dose at the Cu layer by 50% so that the filter could be used at 2 m with a safe margin. Several samples were made of various thicknesses to allow the filtering to be adjusted. The next section describes the measurement of the 2 µm Al/0.9 µm Cu transmission response.

III. EXPERIMENTAL DESCRIPTION

An intense, repeatable, continuum spectrum was required in order to determine precisely the filter transmission response continuously across the Cu L-edge at 932.7 eV. A single beam of the Janus laser, part of the LLNL Jupiter laser facility, was used to irradiate a mid-Z mixed target to emit strong M-shell x-rays in this energy band. The mixture of target materials was picked to fill in the emission features to generate a quasi-continuum from 0.5 – 2 keV. The target consisted of a co-mix of In-Ag-Pd of 0.89 µm thickness coated onto a thin 0.5 µm polypropylene (C_3H_6) foil. The laser parameters were nominally 45 J of 527 nm wavelength light in a 400 ps (FWHM) laser pulse. The 10-90% risetime was 200ps giving a trapezoidal pulse shape. The laser was focused on the metal side of the foil with an *f*6.7 aspheric lens to a 45 µm diameter focal spot and at a 44° angle of incidence from target normal. This gave an irradiance of 3.4 × 10^{15} Wcm^{-2}. The laser energy, pulse shape and focal quality were measured on every shot.

Two 2400 line/mm variable-spaced, flat-field grating spectrometers measured the x-ray emission from the irradiated co-mix foil. A survey spectrometer with a Kentech x-ray streak camera viewed the x-ray emission from behind the target at close to normal incidence and monitored the x-ray duration and emission intensity.[6] The x-ray duration was found to be consistently shorter than the laser pulse. A second high resolution grating spectrometer (HRGS), $\lambda/\Delta\lambda$ > 1000, was operated with a 25 µm slit and used a high dynamic range liquid-Nitrogen-cooled, back-thinned CCD detector.[8,9] The CCD had a 1340 × 1300 pixel array with each pixel 20 × 20 µm^2 dimension. This instrument viewed the front of the target at ~ 17° from the surface. A 150 nm Al foil was placed after the slit to prevent scattered laser light from entering the spectrometer. A filter wheel was installed between the spectrometer slit and the Al foil and was used to measure the transmission response of the 2 µmAl/0.9 µm Cu filter. The filter could be moved in and out sequentially from shot to shot to compare the x-ray source repeatability.

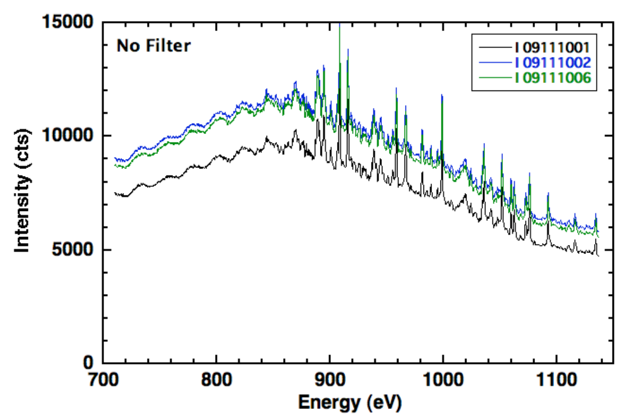

FIG. 2. Three x-ray spectra recorded from In-Ag-Pd co-mix targets on separate laser shots. Laser parameters were held constant for all shots. No Al/Cu filter is used for these shots.

A series of many shots was conducted to optimize the spectrometer alignment to maximize the x-ray signal as well as tune the laser parameters. Six laser shots were taken on Janus where the laser parameters were kept constant to a close tolerance. Laser energy was 44.9 J with a 1σ of 1.1J and pulse duration was 411 ps (FWHM) with a 1σ of 10 ps. The focal spot was nominal at best focus at 45 µm diameter. The spectrometer dispersion was calibrated by using H-like and He-like oxygen transitions emitted from a Mylar ($C_{10}H_8O_4$) target.[8] Figure 2 shows 3 laser shots where the filter to be calibrated was not in the path. Below 900eV photon energy the emission is relatively smooth while line features become apparent above 900 eV. The data shown is uncorrected for the 150 nm Al filter and the other calibration factors of grating and CCD response. Overall the emission is very repeatable with 2 shots matched within 3% in intensity and the third shot is lower by 17%. Further analysis reveals that the spectral content across the energy range is also constant to ±1% for all shots.

Figure 3 is the repeat with the 2 µm Al/0.9 µm Cu filter in. The x-ray signal is reduced by more than one order of magnitude with a further sharp drop at ~930 eV indicating the Cu L-edge.

Again the x-ray emission from two laser shots is found to be very close within 4% while the third is low by 40%. The spectral content again remains constant in the energy range of interest but with a larger ±3% statistical variation due to the lower x-ray signals with the filter in. Overall the statistical effect of the lower signals shots, one in each case, is very small.

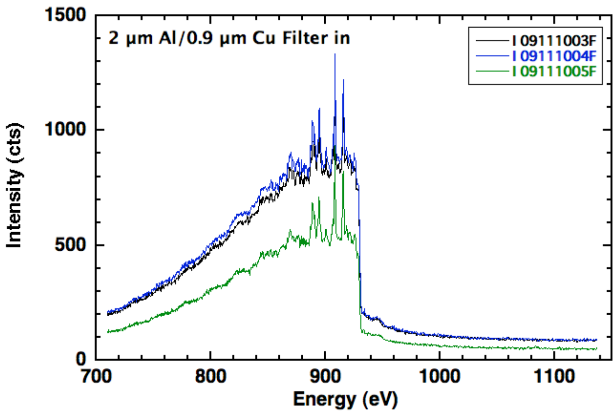

FIG. 3. A series of three x-ray spectra recorded from In-Ag-Pd co-mix targets on separate laser shots. Laser parameters were held constant for all shots. The 2 µm Al/0.9 µm Cu filter is in and shows the effect of the Cu L-edge at ~930 eV.

Figure 4 shows the resultant filter response extracted from Figures 2 and 3. Figure 4 uses all 6 spectra to generate the filter response data. The data has not been smoothed or processed and shows the main expected features. The filter response rises as a function of energy due to the reduced absorption in the Al and Cu filters. At ~930 eV the Cu L-edge results in strong attenuation. The filter response drops to a low value then continues to gradually rise. There is a gradual roll-off in the region above and below the L-edge. This is not observed in the CXRO data.[5] The other main difference is that the measured transmission at 1 keV is approximately 1% and almost 2 orders of magnitude higher than the CXRO data. Some fine, sharp peaks in the transmission curve at 900eV are from the variation in the emission line

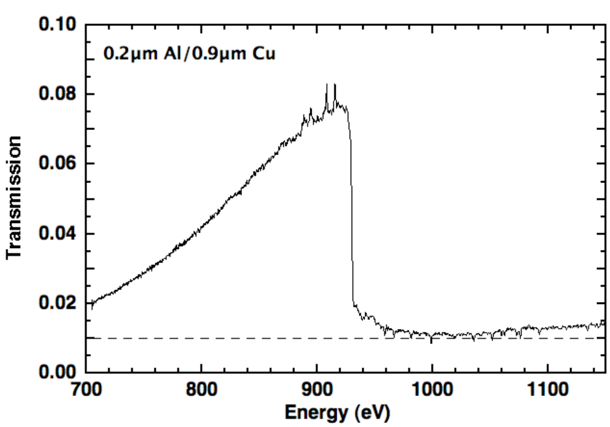

FIG. 4. Filter transmission response for 2 µm Al/0.9 µm Cu. The Cu L-edge at ~930 eV is clear. Horizontal dashed line at 1% transmission indicates the minimum filter response achieved at photon energy of 1 keV.

structure in the source spectrum from shot-to-shot. The roll-off at the L-edge is found in the work by DelGrande[10] which is also referenced by Henke *et al.*.[7] The roll-off above the L-edge is a result of EXAFS as reported in ref 10 and has been measured in other recent Cu filter calibration.[11] The latter reports that a 0.68 µm Cu filter has a transmission of 0.6% at 1 keV. A review of x-ray absorption fine structure spectroscopy methods and data has recently been reported.[12] Our transmission measurements are still a little higher than this and there may be other reasons to be considered. The grating instrument line function has measurable wings due to scattering from surface roughness on the gratings: However, this becomes noticeable at less than 1% intensity of the line peak and can be discounted. Another possibility is that second order reflection of 2 keV photons is being added to the first order signal observed here. This is possible and a detailed calibration of the instrument response is under way. We would still expect this to contribute less than 0.4% to the value measured in Figure 4. The last and most likely contribution to the observed filter transmission at 1 keV is from holes or porosity introduced from the Cu coating process onto the 2 µm foil. If approximately 1% of the area of the filter had small holes then this would be a 0.01× multiplier on the ~50% Al filter transmission at 1 keV to give an added 0.5% transmission.

A combination of low-level 2nd order grating reflectivity as well as a degree of porosity in the filter largely explains the higher than expected transmission. We plan to use improved filters for the LCLS experiment. We would still expect that the EXAFS structure would limit the maximum attenuation factor to be β~50 and so additional ways of reducing the FEL beam intensity after the gas cell would need to be considered.

V. ACKNOWLEDGMENTS

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